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DESIGN OF A NEW CONTRACTION, WIDE ANGLE DIFFUSER AND FLOW MANIP--ETC(U)
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MELBOURNE, VICTORIA

Aerodynamics Technical Memorandum 340

# DESIGN OF A NEW CONTRACTION, WIDE ANGLE DIFFUSER AND FLOW MANIPULATORS FOR THE LOW SPEED WIND TUNNEL

J.B. WILLIS

and

I.A. HUNT





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# DESIGN OF A NEW CONTRACTION, WIDE ANGLE DIFFUSER AND FLOW MANIPULATORS FOR THE LOW SPEED WIND TUNNEL

by

J.B. WILLIS

and

I.A. HUNT

SUMMARY

It is over forty years since the ARL low speed wind tunnel was built, and the quality of the flow in the test section is inadequate by today's standards. This memorandum describes the design of a new contraction, wide angle diffuser and flow manipulators, to improve the flow in this tunnel. These modifications should substantially improve the velocity distribution and reduce turbulence levels with only a small reduction in top speed of the tunnel. A useful increase in the length of the test section has also been obtained.



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## CONTENTS

## NOTATION

| | |
|---|---|
| A | area ratio of diffuser - Figure 4 |
| C | contraction ratio |
| K | pressure loss coefficient, $\Delta p / \frac{1}{2}\rho U^2$ |
| L | length; total length of contraction |
| l | cell length of honeycomb - Figure 3 |
| M | mesh size - Figure 3 |
| O.A.R. | open area ratio of screen - Figure 3 |
| R | radius of equivalent circular section |
| U | mean velocity, axial (x-) direction |
| $\Delta U$ | non-uniformity in U |
| V, W | mean velocities, transverse (y-, z-) directions |
| $\hat{u}$, $\hat{v}$, $\hat{w}$ | r.m.s. turbulence intensity components, in x-, y-, z- directions respectively. |
| $u'$, $v'$ | fractional r.m.s. turbulence intensities, as percentage of U |
| X | position of inflexion point - Figure 6 |
| Y | width of contraction profile - Figure 7 |
| $\alpha$ | mean flow deflection ratio for screen - Appendix 1 |
| $\theta$ | half-angle of diffuser - Figure 4 |

**Subscripts:**

| | |
|---|---|
| e | exit |
| i | inlet |
| s | settling length |
| w | working section |

## 1. INTRODUCTION

The ARL low speed wind tunnel was brought into operation in 1941, and has been in almost continuous operation ever since. However, by modern standards, the tunnel flow suffers from various deficiencies, all well known to tunnel staff. Recent overseas work on improving the quality of flow in similar tunnels has resulted in new designs of contractions of much shorter length, and this has made possible modifications which should greatly improve the flow quality in the low speed tunnel. As with all modifications to existing wind tunnels various restrictions arise which make such modifications a compromise.

This memorandum is intended to record the design of a suitable new contraction, a wide angle diffuser, and flow manipulators. It also indicates the various limitations and some of the choices involved in the modifications. The work described was carried out in 1981.

## 2. PRESENT TUNNEL

The aerodynamic outline of the tunnel is shown in Fig. 1, which is taken from Reference 1, and it will be seen that the contraction ratio is 4:1. Since all dimensions given in Fig. 1 and in other early work, are in Imperial units, it is proposed to retain these units where appropriate. Measurements of the velocity distribution in the test section in 1945[2] are given in Fig. 2 and these indicate almost ±1% velocity variations. References 3 and 4 regard ±0.2% to 0.25% as being acceptable velocity variations, but the RAE 5 metre low speed tunnel has only about ±0.12% variation in velocity, and the design aim was 0.05%[5] In addition, Batchelor and Shaw[6] indicate that there is a separation in the circuit, probably at the entry to the contraction, causing continuous fluctuations of total head of 1% throughout the test section, and with intermittent fluctuations 4.6 inches from a fillet reaching 10%.

Measurements in 1946 of turbulence levels by D.C. Collis and M.J. Williams indicate, at a mean velocity of 100 ft/sec., u' = 0.2 at the centre to u' = 0.75 at a distance 7" from the wall, and v' = 0.75 at a distance 15" from the south wall. The very low frequency oscillations noted by Batchalor and Shaw may add to these figures, depending on the low-frequency cutoff point in the measurements.

Tunnel power has been increased and a new fan fitted since the above work was carried out, but it is unlikely that the low quality has changed. It seems, from the above evidence, that the flow quality is unacceptable by current standards for the main low speed test facility in this country, and that it should be improved.

## 3. METHODS OF IMPROVING THE QUALITY OF FLOW

The initial response is to fix the contraction and install screens in the settling chamber. However, to fix the contraction in a tunnel of this size is far from easy, and may not be practically possible. The losses from screens would also be large, owing to the small contraction ratio. (Appendix 1 shows that to achieve the minimum acceptable mean flow standards, an increase in total circuit losses of 40% and so a drop in cop speed of more than 10% would be needed. To achieve RAE standards, a drop of 15% would be incurred).

Thus a new contraction is required, and if the contraction ratio could be increased, losses from screens would be greatly reduced. Increasing the contraction ratio would also help reduce the risk of wakes persisting around the tunnel circuit, and Ref. 4 states that screens are necessary for the same purpose. Finally, inspection of Fig. 1 shows that the test section is too short by modern standards, and should be lengthened.

An alternative approach is that used in Ref. 7 which does not use screens and, in fact, points out that screens get dirty and can do more harm than good. The method in reference 7 relies on the use of horizontal splitters, adjusting turning vanes etc. This approach would require large amounts of tunnel time, which is not likely to be available at ARL for some years, and it does nothing to help the other problems outlined above.

Thus, the conventional approach of wide angle diffuser, new modern honeycomb screens, settling chamber, new contraction, and increased length of test section is indicated.

It was found that the maximum practical increase in horizontal width of the tunnel settling chamber was 3 ft. per side. Beyond this, extensive structural alterations to the building would be needed, thus increasing the cost very substantially. In addition, the dual test section travelling arrangement becomes very difficult to achieve. With a 3 ft. extension, excavating the floor is not required, and major rebuilding of the roof is avoided. Thus, the practical limit for a new contraction is

$$C = 4 \times \left(\frac{24}{18}\right)^2 = 7.111 \text{ or } \frac{1}{(.375)^2}$$

Although a contraction ratio (C) of about 10:1 would be preferred, 7.1 is a reasonable value for a tunnel of this size and type. C could be increased to 7.9 by ignoring geometrical similarity and running out the fillets to a rectangular settling chamber. This introduces the possibility of additional secondary flows and seems too risky for the gain achievable. Further, the RAE 5 metre tunnel uses 7.6:1 and achieves good quality flow.

Thus, although contraction ratio is important, there seems no practical way to achieve a ratio greater than 7.1 without major structural alterations to the existing building.

Fig. 3 shows the general arrangement of the proposed new configuration compared with the existing one. Of course, the allocation of space between diffuser, contraction, settling length, and test section extension is a matter of compromise. It appears that a satisfactory arrangement can be obtained, and details are given in the following sections.

## 4. WIDE ANGLE DIFFUSER

The design of the wide angle diffuser is based on References 8 and 9, and Figures 4 and 5 are taken from the latter paper. Referring to Fig. 4, with $2\theta = 44°$ and $A = 1.8$, one screen should be adequate and from Fig. 5, a total diffuser screen loss $K_{SUM} = 1$ should suffice. Spacing of the screens may be calculated from Ref. 8 but, from experience, a screen about 2 ft. from the start of this diffuser may be needed and at the very least, provision for such a screen is required. It is well known that pilot tunnel tests, even with deliberately thickened boundary layers, may not prove a reliable guide to the behaviour of the actual full scale tunnel, which may well have some upstream flow disturbance affecting the diffuser behaviour.

Since the contraction is about 14 ft.long, it could be made in two pieces, so that with a diffuser length of 7 ft, the longest pieces to be installed would not exceed 7 ft. Alternatively the diffuser could be 7 ft. long after the first screen, and the same convenience of installation is retained.

## 5. CONTRACTION DESIGN

Recent work on the design of contractions includes that of Chmielewski[10], Morel, Borger[12], and Mikhail[13]. The most recent work is that of Mikhail, and his designs provide very short contractions, and so have been used here. The other design included here is that of Morel, which uses two cubics and is simple to calculate. This design is the next shortest, and has some experimental justification in the work of Rouse and Hassan[14] back in 1949.

All the contractions considered are for axisymmetric contractions, and uncertainty must exist when applied to an irregular octagon.

Three Morel type contractions are shown in Fig. 6. These are for length (L) to inlet radius ($R_i$) = 1.70, and with the point of inflection at 0.4, 0.5, and 0.6 L. The overall length of these contractions is around 19.3 ft. On the same figure are shown three Mikhail contractions for inlet length $L_i$ = 0.60, exit length $L_e$ = 0.45 (the shortest possible contraction), $L_i$ = 0.75, $L_e$ = 0.50; $L_i$ = 0.75, $L_e$ = 0.60. Here

$$L_i \text{ (or } L_e) = \frac{\text{inlet (or exit) length}}{\text{inlet radius}},$$

where inlet (or exit) length is the length from inlet (or exit) to inflection point.. Also included in Fig. 6 is the existing contraction.

With regard to minimum values of $L_i$ and $L_e$, Ref. 11 should be consulted, but an $L_e$ of 0.50 seems indicated. This should be adequate, with an upstream extension of 4 ft. added to the test section. Should this test section extension be deleted, the value of $L_e$ would have to be reconsidered. Inlet length is also variable, and according to Mikhail relaminarization of the boundary layer may occur if $L_i$ is too small, and an increase in $L_i$ or surface roughness may be needed to overcome this. Other factors are Reynolds number, settling chamber length and the change in C from 8.0 (Mikhail's design value) to 7.11. A value for $L_i$ of 0.75 with $L_e$ = 0.50 seems a safe, conservative design.

In practice, $L_i$, $L_s$ and $L_w$ are all related, and depend on the clearance between the contraction and the corner of the second (interchangeable) test section. This clearance depends on the ribbing required to stiffen the steel plate, and may not be known until manufacturers have been consulted. Thus, a longer contraction must be moved upstream, reducing $L_s$ and increasing $L_w$. A contraction of smaller $L_i$ would have greater clearance, and so its entry could move downstream, increasing $L_s$, but being shorter in overall length, having little effect on $L_w$. For this reason, contractions for $L_i$ = 0.75, 0.70 and 0.65, with $L_e$ = 0.50, have been computed, and actual widths are plotted in Fig. 7. It will be seen in Fig. 7 that total length L ranges from about 13 ft. to about 14.2 ft. In Fig. 3, $L_s$ will be around 5 ft., and $L_w$ around 4.5 ft., and although still not accurately defined the figure indicates that an adequate settling length and an adequate test section extension are available. It will be noted that these three contractions are significantly longer than the minimum possible (L = 1.05 $R_i$), ranging from 1.15 to 1.25 $R_i$, and the proposed pilot tunnel tests should clarify the adequacy of their performance.

## 6. FLOW MANIPULATORS

The design of honeycomb and screens is based on Ref. 15 which gives details of pressure losses and turbulence reduction factors for various screens, honeycombs, and combinations of these. In Fig. 3,

the suggested honeycomb has a hexagonal cell of ¼" size length = 1.5 in. and thickness of the material (aluminium) = 0.003 in., while the screens are 20 mesh, wire diameter = 0.009 in., open area ratio = 67%, K = 0.5. Screen $S_2$ is located about 4 inches downstream of the honeycomb, with $S_3$ and $S_4$ located as shown in Fig. 3 - i.e. about 2 ft. apart. Of course, the choice of screens is a compromise since they should have as small a loss as possible to keep tunnel maximum speed high, but a high K is desirable to load the diffuser and ensure it behaves properly, and to reduce turbulence and improve uniformity of flow. Since, for the latter purposes, the effect of screens is $\Sigma$ (1/1+K), while losses are $\Sigma K$, it is preferable to use several rather than one screen. For this reason, provision should be made for both $S_3$ and $S_4$, as in Fig. 3.

Installation, cleaning and repair of screens and honeycomb present problems. Limitations due to the existing building make it almost impossible to mount these devices on frames so that they can be installed, or removed, conveniently. Unless installation is part of initial construction, they will have to be installed from within the tunnel. Repair and cleaning of screens and honeycomb, particularly $S_1$, is going to be very difficult. One possible solution is to use plastic mesh sold as "Bridal Veil", which has mesh and fibre dimensions close to those wanted, and comes in a width of 9 ft. This could be sewn together and many years supply mounted on a roller, with a take up spool on the top or bottom of the tunnel. Using pneumatic clamping and sealing it should be possible to roll a whole new length across as and when needed. Tests are required to check the strength of the material, but a widely-spaced mesh of fine piano wire could be used to support it if necessary.

## 7. TUNNEL PERFORMANCE

The expected improvements in flow quality and the corresponding reduction of maximum tunnel speed are detailed for four proposals in Appendix 1. Estimation of loss increments is not difficult, but estimation of improvements in flow quality is less certain. The basis of the estimates is a combination of direct experimental data, and basic theory.

The first two proposals demonstrate the problems inherent in attempts to modify the existing small-contraction-ratio design. The minimum acceptable mean flow quality is achieved only with an 11% reduction in maximum speed, while the preferred higher quality flow entails a 15% speed reduction. These reductions would significantly reduce the value of the tunnel as a major test facility.

A new contraction profile that provides stable flow is clearly a major gain, and probably justifies the entire proposed system.

The benefits of the higher contraction ratio systems are also clear: the minimum acceptable flow quality is achieved with only a 5% speed reduction, and the higher quality flow can be obtained with a 7% reduction in maximum speed.

It is critical to the proposal that the wide-angle diffuser functions without separating. The screen S1 gives a conservative design, but causes about half the increment in head loss. A smaller speed reduction could be obtained by repositioning or omitting S1, but at this stage, a safer and more profitable approach would be to reduce losses at other circuit components, as discussed in 8, below.

## 8. FURTHER WORK

Pilot tunnel studies of the existing configuration and the new one are to be carried out, and will provide essential verification, or otherwise, of the new design. It may well be necessary to test more than one configuration, since, as stated previously, the contraction designs are all for axisymmetric nozzles. Areas of concern are separation in the wide angle diffuser, in the entry to the contraction, and in the contraction itself, and relaminarization of the boundary layer in the contraction. If the new configuration performs as hoped, consideration should be given to fitting the pilot tunnel with, say, a 10:1 contraction, and perhaps more screens. It would then be a valuable small research tunnel.

The thickness of the existing turning vanes should be reduced, and the behaviour of the corners in the low speed tunnel investigated when time and equipment are available. Gains in tunnel performance by improving the safety screen should also be possible. The fan fairing, which was apparently found to be unsatisfactory in early tests, should be further investigated.

Further, the contraction in the transonic tunnel dates back to about 1954, and its high speed half is "temporary", as the design called for a flexible nozzle and auxiliary suction. By a similar approach to the above, a better and much shorter contraction could be designed and installed, giving increased settling length, a longer working section, and more space for a flexible nozzle in this other major facility.

## 9. CONCLUSIONS

The design of a new contraction, wide angle diffuser and flow manipulators for the low speed wind tunnel has been described. It appears that a test section mean velocity uniformity of ±0.1%, and real improvements in the turbulence level should be achieved, at a cost of about 7% in top speed of the tunnel.

## ACKNOWLEDGEMENT

The authors wish to acknowledge the assistance of D.A. Secomb in solving one of the Mikhail integrals, and for helpful discussions during the work.

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## APPENDIX 1

### Flow quality and head loss estimates

The estimates given are of ratios of absolute quantities, from inlet at the start of the existing settling section, to exit at the end of the contraction - see Figures 1 and 3.

Sources of the estimates are as follows:

for screens, $\frac{\Delta U out}{\Delta U\ in} \simeq \frac{1+\alpha-\alpha K}{1+\alpha+K}$ ; $\frac{V,W out}{V,W\ in} \simeq \frac{1.1}{\sqrt{1+K}} = \alpha$ (reference 3)

$\frac{\tilde{u}\ out}{\tilde{u}\ in} \simeq \frac{1}{1+K}$ ; $\frac{\tilde{v},\tilde{w}\ out}{\tilde{v},\tilde{w}\ in} \simeq \frac{1}{\sqrt{1+K}}$ (reference 15)

for contractions, $\frac{\Delta U\ out}{\Delta U\ in} = \frac{1}{C}$ ; $\frac{V,W\ out}{V,W\ in} = \sqrt{C}$ ;

$\frac{\tilde{u}\ out}{\tilde{u}\ in} \simeq \frac{1}{2C} \sqrt{3(\ln 4C^3-1)}$ ; $\frac{\tilde{v},\tilde{w}\ out}{\tilde{v},\tilde{w}\ in} \simeq \frac{\sqrt{3c}}{2}$

- see reference 3. Diffuser is treated as a reversed contraction. Turbulence equations fail for $C \lesssim 2.5$, faired curve to C=1 was used.

for honeycombs, $\frac{\Delta U\ out}{\Delta U\ in} = 1.0$ assumed ; $\frac{V,W\ out}{V,W\ in} \simeq \frac{\tilde{v},\tilde{w}\ out}{\tilde{v},\tilde{w}\ in}$ assumed

$\frac{\tilde{u},\tilde{v},\tilde{w}\ out}{\tilde{u},\tilde{v},\tilde{w}\ in}$ from data of reference 15. Ratio taken to be proportional to 1/cell aspect ratio i.e.proportional to M/1.

For the proposed honeycomb and screen S2, values are taken directly from the test data in reference 15, which treats the arrangement as a combined unit.

The target values for ratios of proposed to existing flow quality parameters are:

for minimum acceptable mean flow uniformity,
$\Delta U$:0.25 ; V,W : (existing values unknown) ; $\tilde{u}$, $\tilde{v}$, $\tilde{w}$ : 0.20
for high quality mean flow,
$\Delta U$:0.15 ; V,W : - ; $\tilde{u}$, $\tilde{v}$, $\tilde{w}$ : 0.20

The total loss factor for the existing tunnel circuit, referred to the working section, is 0.193.

| SYSTEM EXAMINED | RATIO: QUANTITY OUT / QUANTITY IN | | | | $K_W$ INCR | MAX SPEED m/s |
|---|---|---|---|---|---|---|
| | $\Delta U$ | V,W | $\tilde{u}$ | $\tilde{v},\tilde{w}$ | | |
| EXISTING TUNNEL : 4:1 CONTRACTION, 4:1 ASPECT RATIO HONEYCOMB, NO SCREENS | .25 | 1.4 | .43 | 1.2 | 0 | 107 |
| EXISTING TUNNEL AS ABOVE, WITH 2 - K = .66 SCREENS IN SETTLING SECTION | .062 | 1.0 | .15 | .76 | .082 | 95 |
| RATIO: PROPOSED/EXISTING | .25 | .70 | .36 | .61 | | .89 |
| EXISTING TUNNEL AS ABOVE, WITH 3 - K = .66 SCREENS IN SETTLING SECTION | .031 | .88 | .092 | .59 | .12 | 90 |
| RATIO: PROPOSED/EXISTING | .125 | .61 | .22 | .47 | | .85 |
| PROPOSED SYSTEM: 7:1 CONTRACTION, 6:1 ASPECT RATIO HONEYCOMB, SCREENS S1, S2, S3 ONLY, EACH K = 0.5 | .054 | .65 | .062 | .40 | .034 | 101 |
| RATIO: PROPOSED/EXISTING | .21 | .45 | .14 | .32 | | .95 |
| PROPOSED SYSTEM WITH SCREEN S4 (K = 0.5) INCLUDED | .032 | .57 | .040 | .34 | .044 | 100 |
| RATIO: PROPOSED/EXISTING | .13 | .40 | .093 | .27 | | .93 |

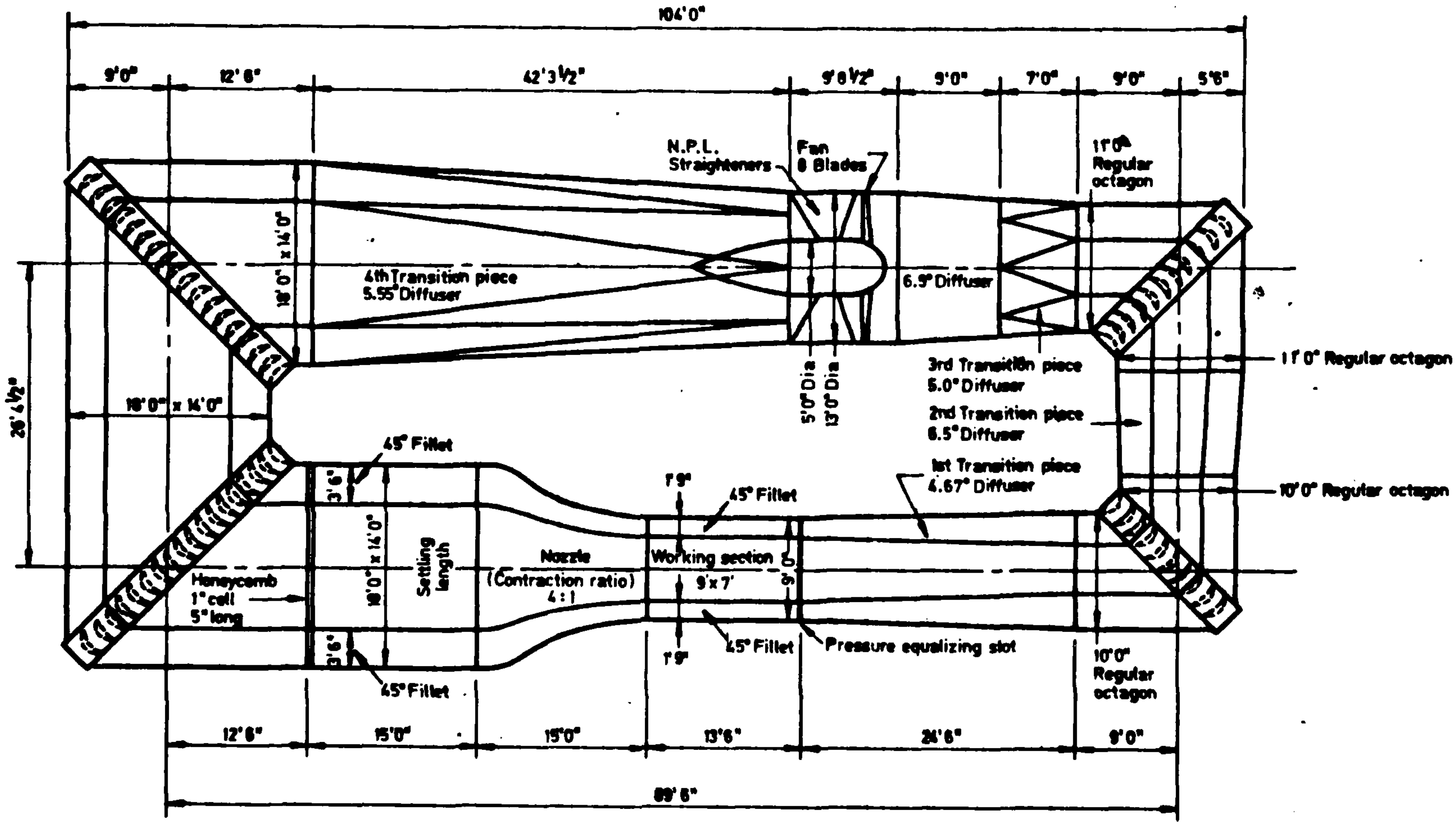
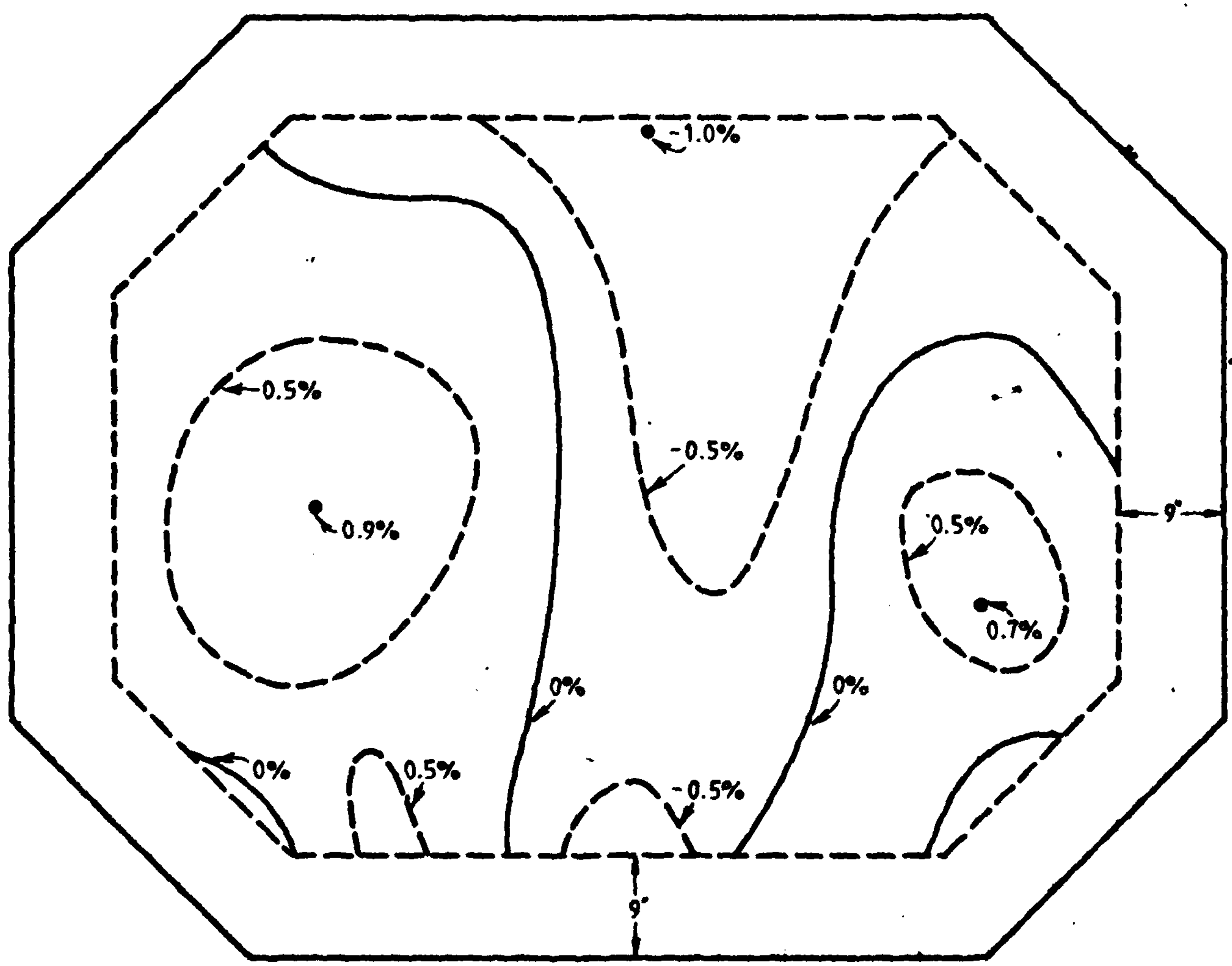



FIG. 1 AERODYNAMIC OUTLINE - 9' X 7' WIND TUNNEL




Percentage variations from mean velocity at 250f.p.s.

FIG. 2 VELOCITY CONTOURS IN 9' X 7' TUNNEL WORKING SECTION

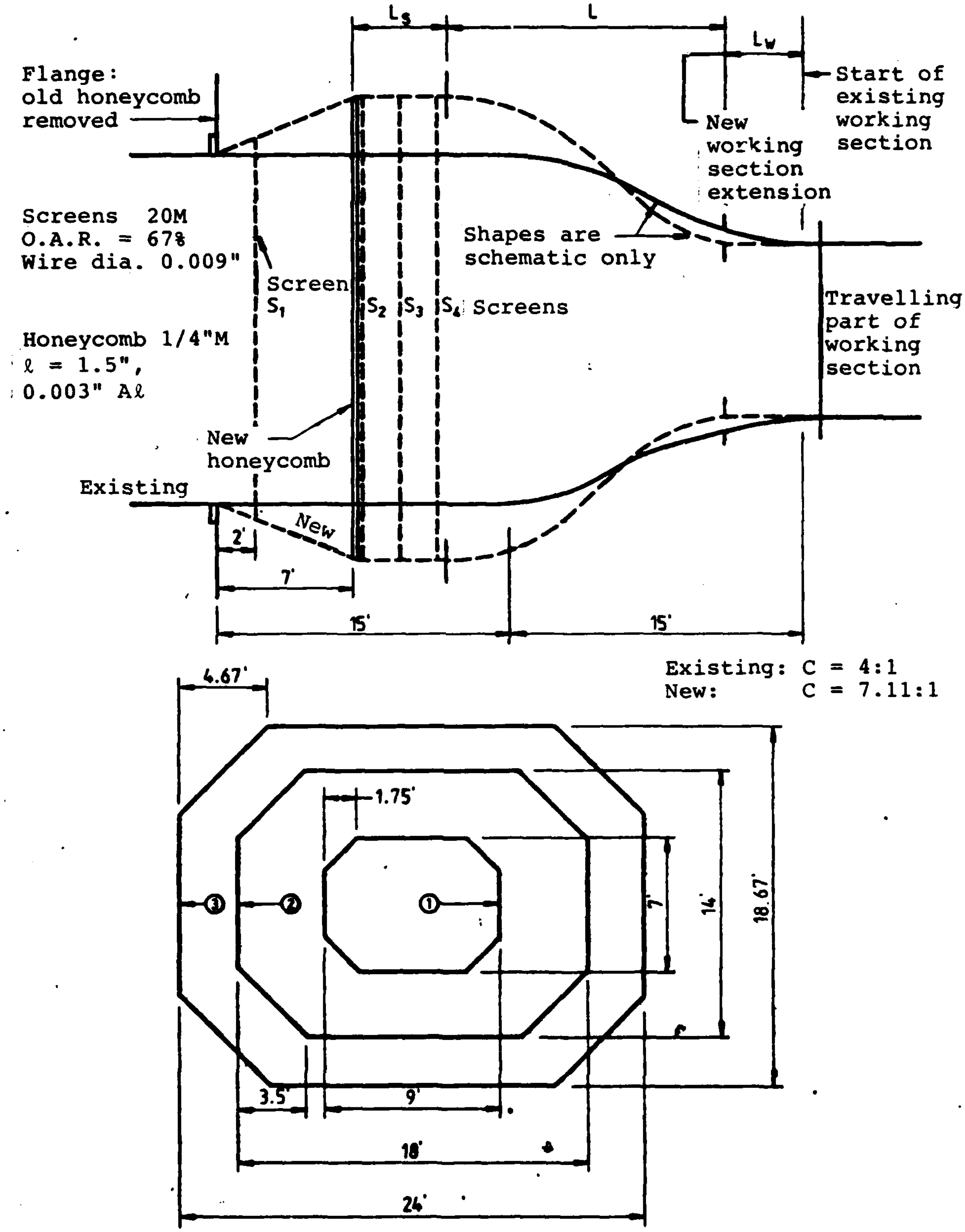



FIG. 3 PROPOSED NEW CONFIGURATION

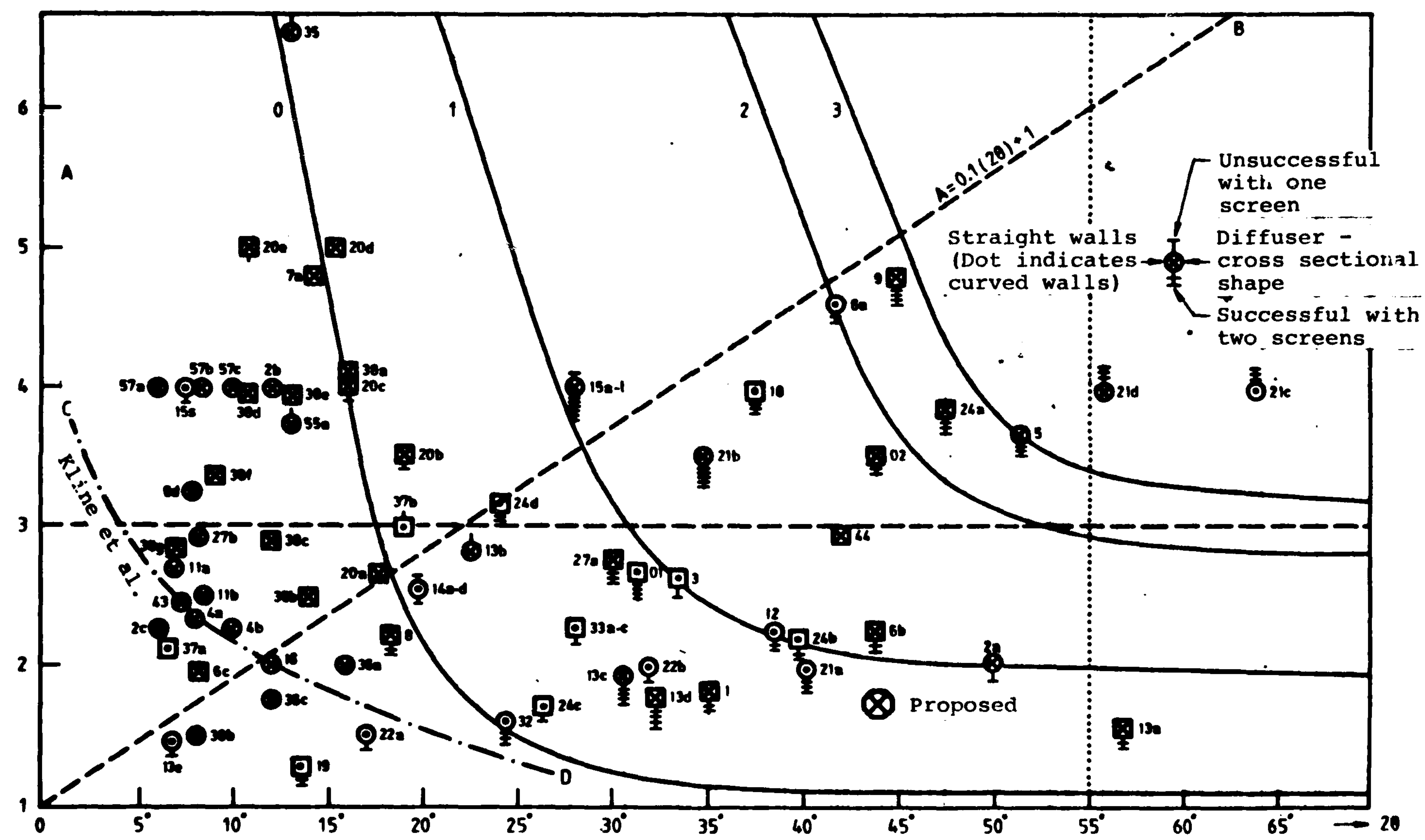



FIG. 4 A vs 2θ FOR DIFFUSERS WITH (OR WITHOUT) SCREENS

[From Mehta, Ref. 9]

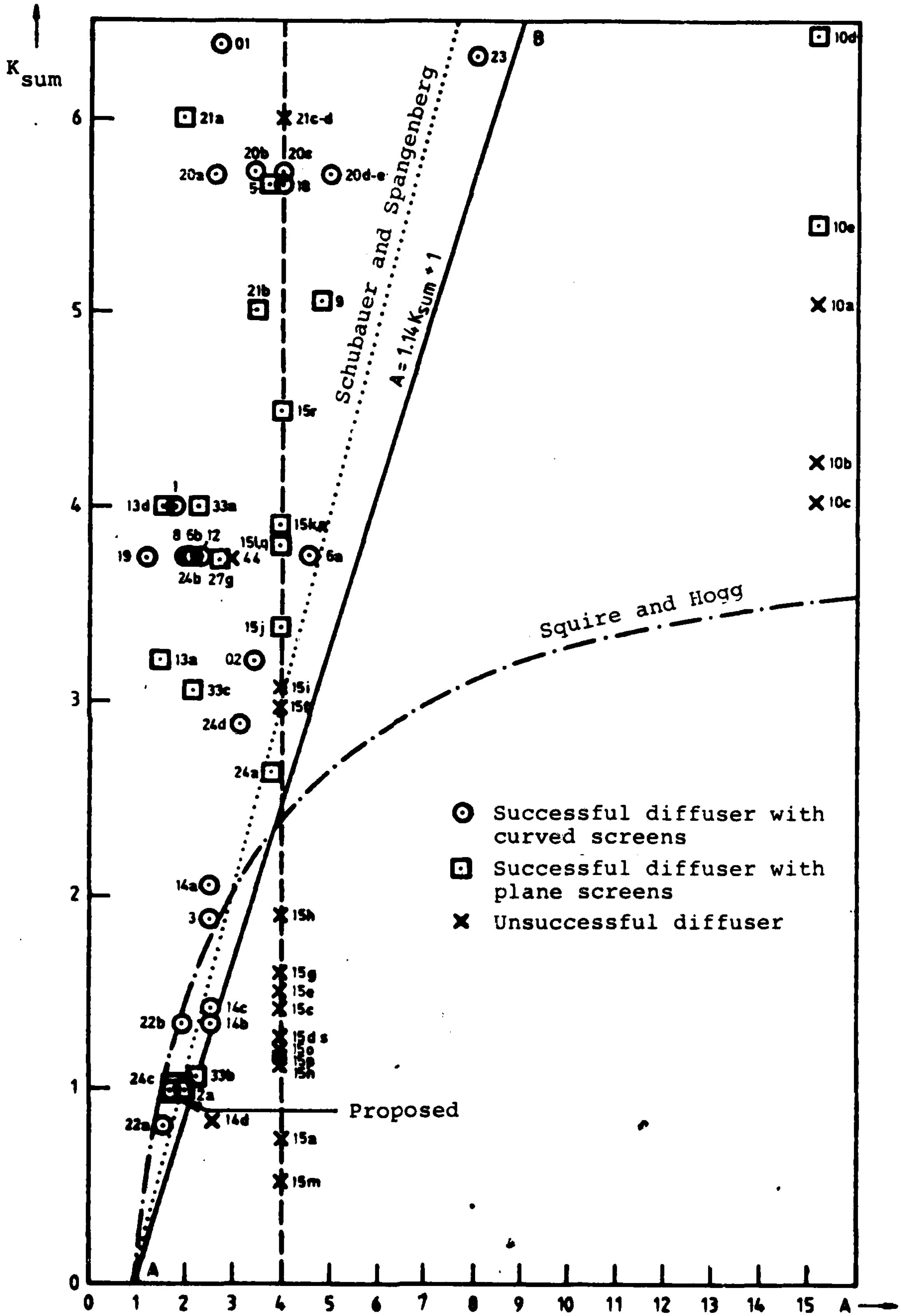



FIG. 5 $K_{SUM}$ vs A FOR DIFFUSERS WITH SCREENS
[From Mehta, Ref. 9]

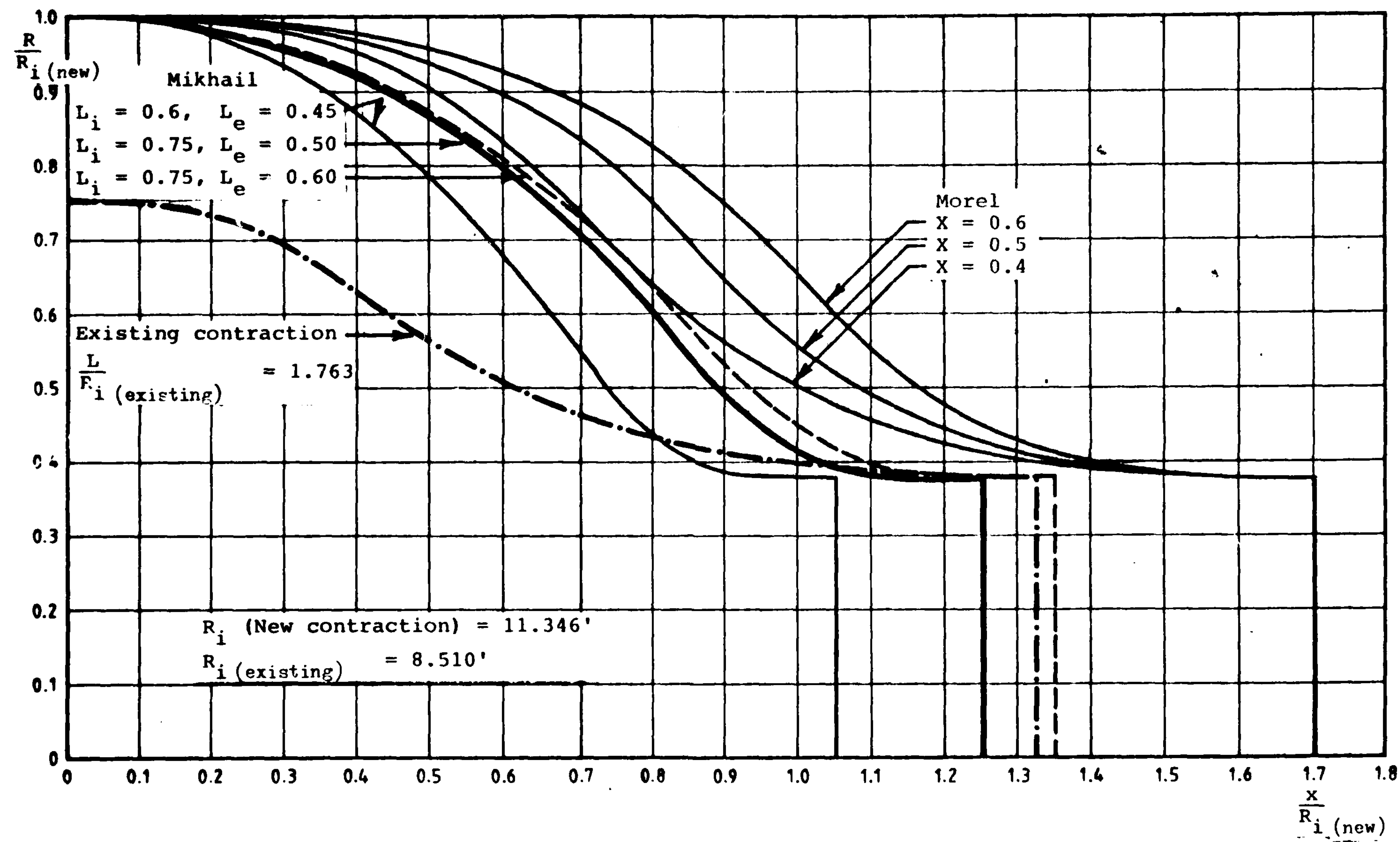



FIG. 6 CONTRACTION DESIGNS: EQUIVALENT CIRCULAR CROSS-SECTION

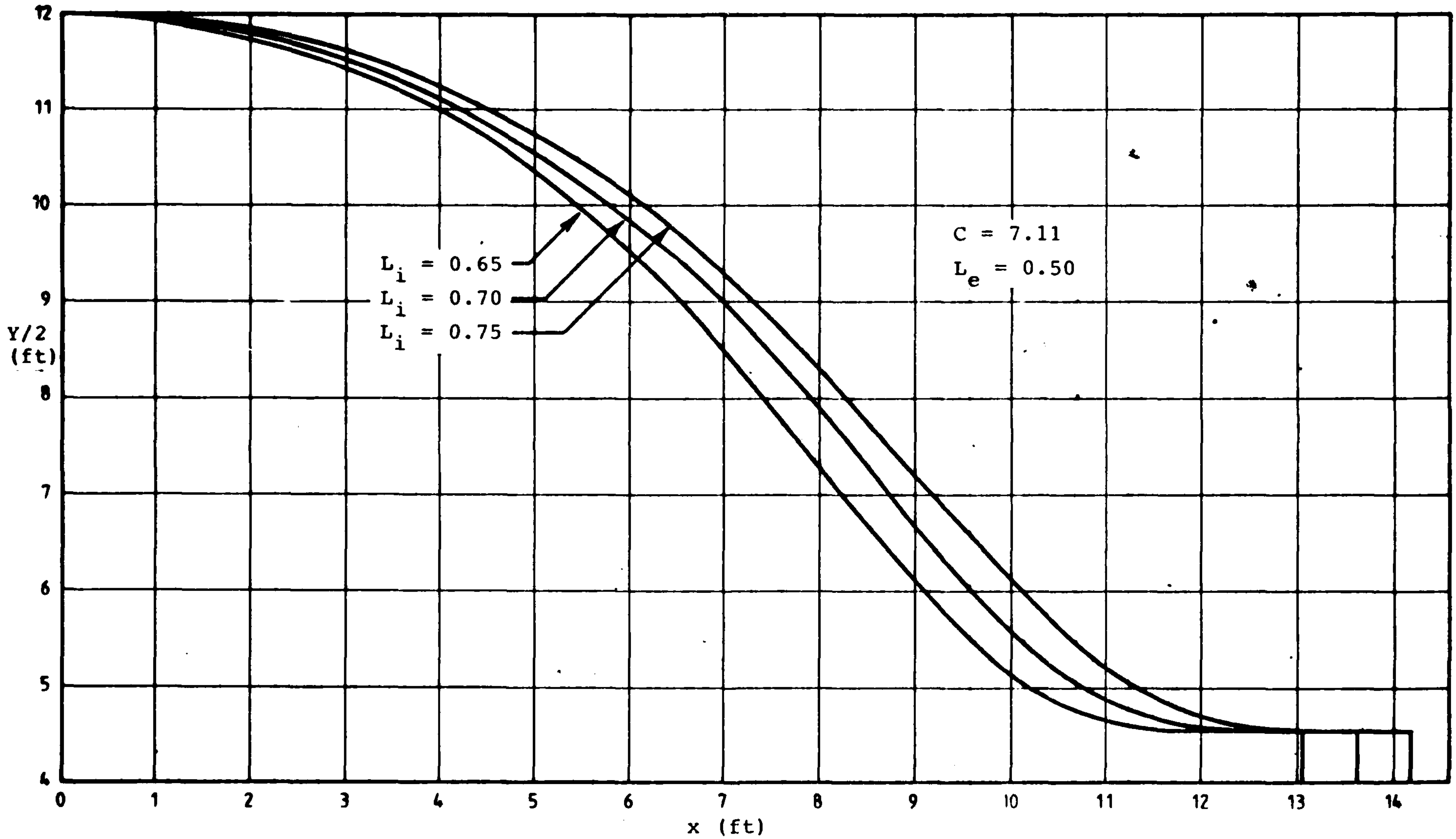



FIG. 7 THREE MIKHAIL CONTRACTIONS: PLAN DIMENSIONS

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| 14. Descriptors | | 15. COSATI Group |
|---|---|---|
| Subsonic wind tunnels | Fluid flow | 1402 |
| Subsonic flow | Turbulence | 0101 |
| Wind tunnel nozzles | Uniform flow | |
| Diffusers | Wide angle diffusers | |
| Screens (woven materials) | | |
| Flow distribution | | |

16. Abstract

It is over forty years since the A.R.L. low speed wind tunnel was built, and the quality of the flow in the test section is inadequate by today's standards. This memorandum describes the design of a new contraction, wide angle diffuser and flow manipulators, to improve the flow in this tunnel. These modifications should substantially improve the velocity distribution and reduce turbulence levels with only a small reduction in top speed of the tunnel. A useful increase in the length of the test section has also been obtained.

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| 16. Abstract *(Contd)* | | |
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